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Nonvanishing Energy Scales at the Quantum Critical Point of $CeCoIn_5$

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Heat and charge transport were used to probe the magnetic field-tuned quantum critical point in the heavy-fermion metal $CeCoIn_5$. A comparison of electrical and thermal resistivities reveals three characteristic energy scales. A Fermi-liquid regime is observed below T_{FL}, with both transport coefficients diverging in parallel and $T_{FL} \to 0$ as $H \to H_c$, the critical field. The characteristic temperature of antiferromagnetic spin fluctuations, T_{SF}, is tuned to a minimum but *finite* value at H_c, which coincides with the end of the T-linear regime in the electrical resistivity. A third temperature scale, T_{QP}, signals the formation of quasiparticles, as fermions of charge e obeying the Wiedemann-Franz law. Unlike T_{FL}, it remains finite at H_c, so that the integrity of quasiparticles is preserved, even though the standard signature of Fermi-liquid theory fails.

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The ongoing search for universality in systems tuned to a quantum critical point (QCP) has led to the discovery of a host of fascinating condensed matter systems which deviate from Landau's Fermi liquid (FL) theory of metals. With dominant characteristic energy scales which become small or vanishing at a QCP, the Fermi energy no longer dictates the form of low-energy excitations, and so-called non-FL behaviour prevails [1].

The extent to which zero-temperature critical fluctuations influence the fermionic degrees of freedom at a QCP is an open question. For instance, two leading theories predict quite different fates for the FL state. In the weak-coupling quantum spin density wave (SDW) scenario [2, 3], fluctuations are concentrated at hot spots on the Fermi surface, leading to a "mild" breakdown of FL theory: at the QCP, the electronic specific heat C/T shows a square-root divergence but remains finite in the $T \to 0$ limit [4], reflecting the fact that, below a *finite* characteristic temperature, the FL state is recovered on part of the Fermi surface. This scenario appears to be realized in $CeNi_2Ge_2$ [5] and $CeIn_3$ [6], and is usually accompanied by a $T^{3/2}$ dependence of resistivity [4]. In the strong-coupling "locally" critical scenario [7, 8], fluctuations are thought to completely cover the Fermi surface, causing a logarithmic divergence of C/T and a vanishing characteristic temperature [8]. This leads to a "strong" breakdown of the quasiparticle picture [8]. This scenario is thought to be realized in $YbRh_2Si_2$ [5, 9] and $CeCu_{5.9}Au_{0.1}$ [10], and is characterized by a T-linear resistivity at the QCP.

The comparison of heat and charge transport is one of a few experimental studies which can give access to information on the spectrum of critical fluctuations *and* their influence on fermionic excitations. A quintessential test of FL theory is the Wiedemann-Franz (WF) law, which states that the ratio of thermal (κ) to electrical (σ) conductivities is a universal constant in the $T \to 0$ limit: $\kappa/\sigma T = L_0 \equiv \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$. A violation of this law would imply a profound breakdown of the FL model, in the sense that low-lying excitations would no longer be quasiparticles of charge e obeying Fermi statistics. In addition, a comparison of $\kappa(T)$ and $\sigma(T)$ at finite temperatures provides information about the momentum and energy dependence of magnetic fluctuations, through their effect on quasiparticle scattering, and thus can also be used to probe the nature of a QCP.

In this Letter, we apply this approach to a system with tunable critical behaviour in order to (i) test the WF law at the QCP and (ii) track the fluctuation spectrum as a function of tuning parameter. The material, $CeCoIn_5$, is a heavy-fermion metal which exhibits a magnetic field-tuned QCP characterized by a divergence in transport [11] and thermodynamic [12] quantities at a critical field H_c. With a readily accessible and continuous control parameter, this extremely clean, stoichiometric material offers a unique opportunity to study criticality via heat transport over the entire temperature range of relevance.

Heat and charge transport measurements were performed as described previously [13, 14] on single crystals of $CeCoIn_5$ grown by the self-flux method [15] with $\rho_0 \simeq 0.1$ $\mu\Omega$ cm ($H \to 0$), for currents parallel to [100] and field parallel to [001]. A comparison of heat and charge resistivities reveals that scattering in $CeCoIn_5$ is practically identical to that observed in antiferromagnetic $CeRhIn_5$ above its ordering temperature, T_N [13], both being governed by a comparable spin-fluctuation scale T_{SF}. This confirms the magnetic nature of the QCP in $CeCoIn_5$ [16]. Moreover, in $CeCoIn_5$ T_{SF} is tuned by magnetic field towards a minimum but *finite* value at H_c, which accounts for the departure at low T from the T-linear resistivity. We show that, despite the presence of a non-FL $T^{3/2}$ power law in both electrical and thermal re-

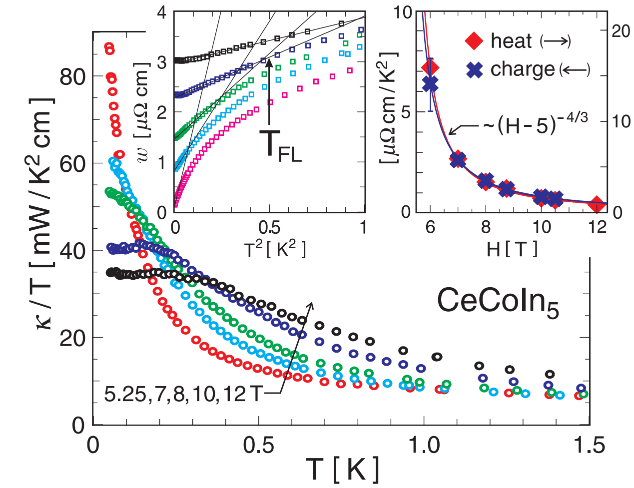

FIG. 1: Thermal conductivity of $CeCoIn_5$, plotted as κ/T vs T (main panel) and as electronic [17] thermal resistivity $w = L_0T/\kappa_e$ vs T^2 (left inset), for $H \parallel [001]$. The data in the left inset, offset for clarity, is for $H = 6$, 7, 8, 10 and 12 T (bottom to top); lines are linear fits valid up to $T = T_{FL}$, the Fermi-liquid temperature, marked by an arrow for $H = 10$ T. Right inset: field dependence of the T^2 Fermi-liquid coefficients of charge and heat transport.

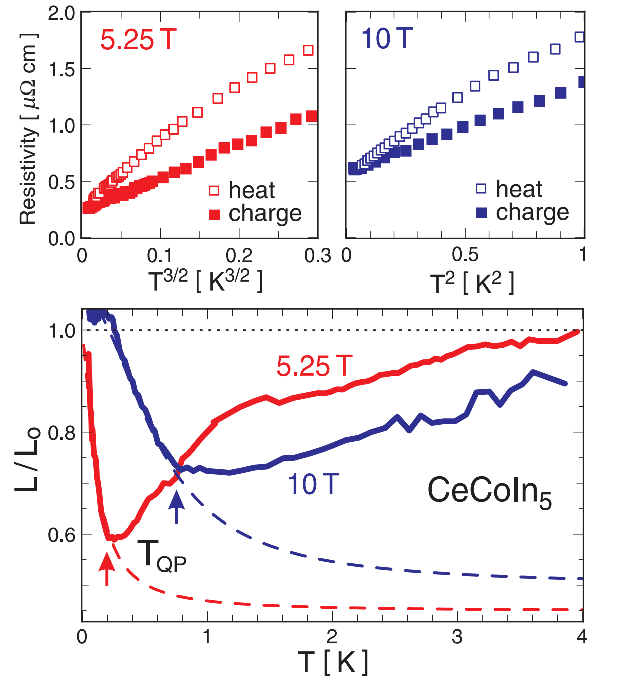

FIG. 2: Upper panels: comparison of thermal ($w(T)$; open symbols) and electrical ($\rho(T)$; solid symbols) resistivities at the critical field (5.25 T), plotted vs $T^{3/2}$ (left), and in the FL regime (at 10 T), plotted vs T^2 (right). Lower panel: normalized Lorenz ratio, $L/L_0 \equiv \kappa_e/L_0\sigma T \equiv \rho(T)/w(T)$, vs T. Dashed lines show the ratio of the low-temperature power laws, namely $(\rho_0 + aT^\alpha)/(w_0 + bT^\alpha)$, with $\alpha = 3/2$ and 2, for 5.25 and 10 T, respectively. The quasiparticle temperature, T_{QP}, marked by arrows, is defined as the temperature below which $L(T)$ starts to rise, aiming towards unity.

sistivities at H_c, the WF law is still obeyed in the $T \to 0$ limit. This reveals a "mild" breakdown of FL theory in $CeCoIn_5$ consistent with the SDW-model.

Fermi-liquid temperature, T_{FL}. Previous resistivity measurements [11] have shown that a FL regime develops in $CeCoIn_5$ above its superconducting $H_{c2} = 5$ T, characterized by $\Delta\rho \equiv \rho - \rho_0 = AT^2$, with A diverging as $A(H) \propto (H - H_{c,A})^{-\alpha}$, where $H_{c,A} = 5.1$ T and $\alpha = 1.37 \approx 4/3$. Fig. 1 presents an analysis of $\rho(T)$ and $\kappa(T)$ data obtained from a new sample with resistivity characterized by very similar fit parameters, namely $H_{c,A} = 5.0 \pm 0.1$ T and $\alpha = 1.29 \pm 0.1$. As a function of field, κ/T evolves from an almost divergent behaviour at 5.25 T towards more FL-like saturation at higher fields. This is seen more clearly by plotting the electronic [17] thermal resistivity $w \equiv L_0T/\kappa_e$ vs T^2, in the left inset of Fig. 1. This plot reveals a T^2 dependence of $w(T)$ (*i.e.* $\Delta w \equiv w - w_0 = BT^2$), observed below a characteristic temperature T_{FL} as high as 1.0 K at 12 T, which decreases steadily, so that $T_{FL} \to 0$ at H_c (see Fig. 3).

The field dependence of the slope B, which represents the contribution of electron-electron (e-e) scattering to thermal transport (analogous to A), is shown in the right inset of Fig. 1, together with $A(H)$. It is clear that $B(H)$ has the *same critical field dependence* as $A(H)$. Specifically, B is best fitted by a function $B(H) \propto (H - H_{c,B})^{-\beta}$ with parameters $H_{c,B} = 5.0 \pm 0.2$ T and $\beta = 1.34 \pm 0.1$, so that $H_{c,A} = H_{c,B} \equiv H_c = 5.0$ T and $\alpha = \beta$ (within error). Therefore, $A(H)$ and $B(H)$ differ only by a *field-independent* factor, $A/B = 0.47 \pm 0.03$. Since the ratio A/B is governed by the **q**-dependence (*i.e.* is sensitive to the angular dependence) of e-e scattering around the Fermi surface [18], this suggests that the anisotropy of quasiparticle scattering in $CeCoIn_5$ is unchanged by the field, even though A itself grows by a factor of 35, from 0.2 $\mu\Omega$ cm/K^2 at 16 T to 7 $\mu\Omega$ cm/K^2 at 6 T.

Quasiparticle temperature, T_{QP}. As we approach the QCP, the ranges of T^2 thermal and electrical resistivities shrink to nothing (*i.e.* $T_{FL} \to 0$), whereupon both $\Delta\rho$ and Δw exhibit a different power-law dependence at low temperature, namely $T^{3/2}$ (see upper panels of Fig. 2). Remarkably, the $T \to 0$ extrapolations of $\rho(T)$ and $w(T)$ *within this non-FL regime* nevertheless converge to satisfy the WF law, so that $\rho_0 = w_0$ (within the $\pm 6\%$ experimental accuracy on the ratio) not only far from H_c (*e.g.* at 10 T) but also right at H_c (*i.e.* at 5.25 T). This reveals that the breakdown of FL theory in $CeCoIn_5$ is not complete: while the expected T^2 dependence of the scattering rate is indeed violated at the QCP, *the integrity of the quasiparticles themselves is nonetheless preserved.*

The overall temperature dependence is best captured by plotting the (normalized) Lorenz ratio, $L/L_0 \equiv \kappa_e/L_0\sigma T \equiv \rho(T)/w(T)$, shown in the lower panel of Fig. 2. The convergence of $\rho(T)$ and $w(T)$ shows up

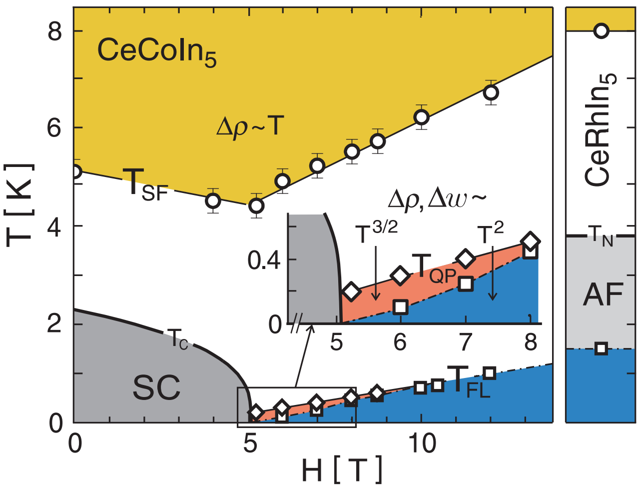

FIG. 3: Evolution of characteristic energy scales in $CeCoIn_5$ vs magnetic field. The Fermi-liquid temperature T_{FL} is the end of the T^2 regime in $w(T)$ (squares). The quasiparticle temperature T_{QP} is the onset of the low-T upturn in $L(T)$ (diamonds). The spin-fluctuation temperature T_{SF} is reached when $\delta(T) = 0$ at high T (circles). Error bars for T_{QP} and T_{FL} are smaller than the size of symbols. Note that $T_{QP} = T_{FL}$ at $H = 10$ T and above. To the right, we also show T_{SF} and T_{FL} for $CeRhIn_5$ (at $H = 0$).

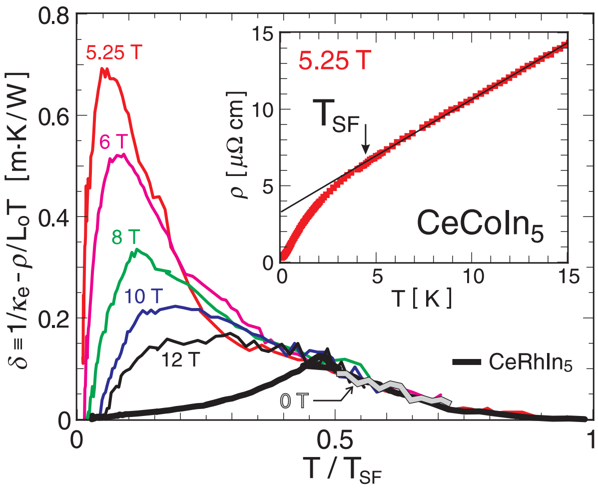

FIG. 4: Difference between electronic thermal resistivity and electrical resistivity of $CeCoIn_5$, labelled δ, as a function of reduced temperature T/T_{SF}, where T_{SF} is obtained by making all curves at different fields (as indicated) match at high temperature. The corresponding data for antiferromagnetic $CeRhIn_5$ in zero field is also shown (thick black line). Inset: temperature dependence of electrical resistivity at the critical field, with arrow indicating the position of T_{SF}. The line is a linear fit to the data above 8 K.

as a rapid upturn in L/L_0 with decreasing T, wherefrom it is aimed at unity. We define as T_{QP} the onset of this upturn, which is also the temperature below which $\Delta\rho$ and Δw have both reached their asymptotic power-law behaviour. *We view T_{QP} as the temperature below which quasiparticles form.* In the inset of Fig. 3, we plot T_{QP} as a function of field. Away from the QCP, for $H \geq 10$ T, T_{QP} coincides with T_{FL}, so that quasiparticles exhibit the standard T^2 behaviour as they form. However, as one approaches the QCP, for $H < 10$ T, the upturn in $L(T)$ starts above T_{FL}, and T_{QP} remains finite as T_{FL} vanishes. Therefore, quasiparticles still form at the QCP of $CeCoIn_5$, even though they do not show the standard FL signature of T^2 resistivity. This is reminiscent of the observation that quantum oscillations are still present at H_c, while standard Lifshitz-Kosevich theory fails [19]. For a complete breakdown of quasiparticles at the QCP, one would need to have seen $T_{QP} \to 0$, in addition to the usual condition $T_{FL} \to 0$. It transpires that *T_{QP} is a new and fundamental temperature scale for quantum criticality.*

Spin fluctuation temperature, T_{SF}. A recent study of $CeRhIn_5$ [13] has shown the usefulness of examining not only the ratio, but also the *difference* between thermal and electrical resistivities, given by $\delta \equiv 1/\kappa_e - \rho/L_0T$ [20]. Physically, $\delta(T)$ is due to those scattering processes in which the energy of the conduction electron is changed but not its direction, thereby affecting κ but not σ [21]. It is plotted in Fig. 4 for both $CeCoIn_5$ and $CeRhIn_5$. We begin by describing its behaviour in $CeRhIn_5$, where the electronic scattering rate was observed to be directly proportional to the entropy of the magnetic system (specifically, $w \propto S_{mag}$, the magnetic entropy) [13].

At high temperature, $\delta(T)$ goes to zero, not because the overall scattering has decreased, for that keeps increasing monotonically with T (tracking S_{mag}), but because direction-conserving processes have become ineffective. This occurs when T exceeds the characteristic temperature T_{SF} of spin fluctuations, which then have insufficient energy to scatter electrons through the thermal layer [21]. We define T_{SF} to be the temperature where $\delta(T) \to 0$ [22]. In $CeRhIn_5$, $T_{SF} \simeq 8$ K [13], the temperature where, interestingly, neutron studies found antiferromagnetic correlations to set in [23]. As temperature is decreased below T_{SF}, $\delta(T)$ starts to rise, and keeps rising until T_N, where it takes an abrupt cusp-like dive, as a gap opens in the fluctuation spectrum upon ordering. At T well below T_N the electron system eventually enters a FL state characterised by: (1) a linear rise in $\delta(T)$ up to $T_{FL} \simeq 1.5$ K, from the T^2 dependence of both w and ρ; (2) a low mass enhancement, with $A = 0.02\ \mu\Omega$ cm/K^2 [13], and (3) the WF law, $\delta(T) \to 0$ at $T \to 0$.

Turning to $CeCoIn_5$, one can see from Fig. 4 that at high temperature $\delta(T)$ curves for all fields can be collapsed onto the $\delta(T)$ curve for $CeRhIn_5$ above T_N, upon normalizing T by T_{SF}. The values of T_{SF} needed for this scaling are plotted in Fig. 3. By inspection, one can see that $CeCoIn_5$ at $\simeq 15$ T is equivalent to $CeRhIn_5$ for $T > 4$ K, in the sense that the two materials have the same $\rho(T)$ and $\delta(T)$, the same $T_{SF} \simeq 8$ K and even the

same $T_{FL} \simeq 1.5$ K. Therefore, *the electrons are scattered by the same antiferromagnetic fluctuations in both materials.* The difference occurs below 4 K: while the magnetic moments in $CeRhIn_5$ order at $T_N = 3.8$ K, they never do in $CeCoIn_5$ where the entropy remains high all the way down to the FL regime, leading to a large mass enhancement, with a coefficient $A = 0.2$ $\mu\Omega$ cm/K^2 (at 16 T) [11], 1 order of magnitude larger than in $CeRhIn_5$.

As the field is decreased towards H_c, T_{SF} steadily drops towards a minimum value of 4.4 K at H_c (see Fig. 3). This shows that the antiferromagnetic fluctuations in $CeCoIn_5$ are indeed tuned by the magnetic field. Note, however, that T_{SF} does not vanish at H_c. This fact is an important new element in our understanding of quantum criticality in $CeCoIn_5$. In particular, it elucidates why the resistivity does not display a single power law at the QCP: as shown in the inset of Fig. 4, $\rho(T)$ at H_c is linear down to 5 K, but then drops as it crosses T_{SF}, to eventually go over to a $T^{3/2}$ dependence.

A finite T_{SF} suggests that the energy of magnetic fluctuations remains finite even at the QCP, as found with neutrons in $CeNi_2Ge_2$ [24], which also obeys the WF law [25] as does $Sr_3Ru_2O_7$ at its field-tuned QCP [26]. Together with a $T^{3/2}$ dependence at H_c, also observed in $CeIn_3$ under both applied field [6] and pressure [27], and in $CeCoIn_5$ under pressures that restore the Fermi-liquid state at low T [28], this is consistent with gaussian-type fluctuations predicted in the SDW model [2, 3, 4]. This presumably indicates that magnetic fluctuations in the $CeIn_3$ planes of $CeCoIn_5$ and in bulk $CeIn_3$ itself have a similar character.

Summarizing our observations, we can state that (1) fluctuations near the field-tuned QCP in $CeCoIn_5$ are antiferromagnetic in nature, as revealed by the scaling of $\delta(T)$ curves for $CeCoIn_5$ relative to $CeRhIn_5$; (2) the characteristic temperature scale of fluctuations, T_{SF}, is tuned to a minimum but non-vanishing value at the QCP; (3) T_{SF} correlates well with the end of the T-linear regime in the electrical resistivity, thus accounting for the lack of a single power law in $\rho(T)$ at the QCP; (4) at H_c, both electrical and thermal resistivities exhibit a $T^{3/2}$ dependence below a second non-vanishing characteristic temperature, T_{QP}; (5) even in the presence of such non-FL behaviour, the Wiedemann-Franz law holds in the $T \to 0$ limit at H_c.

These findings point to a "mild", incomplete breakdown of Fermi-liquid theory in $CeCoIn_5$, characterized by a non-vanishing T_{QP}, the temperature below which fermionic quasiparticles of charge e appear to still form, even at the QCP where the usual T^2 Fermi-liquid regime has shrunk to nothing ($T_{FL} \to 0$). This seems to be in line with the spin-density wave scenario of quantum criticality, even though it requires that the Kondo temperature, effectively removing local moments from the problem, be higher than $T_{SF} \simeq 4$ K, and the single-impurity Kondo temperature in dilute $Ce_{1-x}La_xCoIn_5$ alloys was determined to be ~ 1.5 K [29].

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